Plutonic xenoliths reveal the timing of magma evolution at Hualalai and Mauna Kea, Hawaii

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ABSTRACT

Hawaiian volcanoes evolve through stages that have been delimited by the compositions of their erupted lavas. New in situ ^{238}U-^{230}Th and U-Pb dating of single zircons from leucocratic plutonic xenoliths erupted at Mauna Kea and Hualalai volcanoes, Hawaii, reveals that important episodes of magmatic evolution are not necessarily reflected in the stratigraphy or compositions of erupted lavas. Zircons from Mauna Kea diorites form a heterogeneous population with apparently bimodal ages of ca. 125 ka and ca. 65 ka, suggesting fractionation, intrusion, and crystal recycling about the time of transition of postshield volcanism from basaltic to hawaiitic compositions. Hualalai syenogabbros and diorites record extreme fractionation and generation of alkalic magma at 41 ± 9 ka and 261 ± 28 ka, indicating that alkalic magma was generated ~130,000 yr before the shield to postshield transition inferred from lava stratigraphy, and that coeval evolution of chemically distinct magma reservoirs at shallow and deep levels may have characterized the shield stage. These episodes at Hualalai did not cause eruption of evolved lavas, indicating that extreme differentiation in Hawaiian volcanoes is not necessarily followed by eruption of highly evolved magma.

Keywords: uranium-series method, magma chambers, magmatic differentiation, cumulates, volcanism.

INTRODUCTION

Highly evolved magmas, such as trachytes and rhyolites, are typically volumetrically minor relative to basalts at oceanic volcanoes but are important because they mark decreases in the supply of magma from the mantle (e.g., Clague, 1987) or melting of subvolcanic crust (e.g., Bohrson and Reid, 1998). At Hawaiian volcanoes, eruptions of highly evolved magmas are especially rare and signal the final stages of edifice construction when waning magma supply leads to cooling and extreme fractional crystallization of magma reservoirs (Clague, 1987; Frey et al., 1990; Fodor, 2001; Shamberger and Hammer, 2006). Much of the mass of Hawaiian volcanoes is generated during the tholeiitic shield stage, when a volcano is centered on the hotspot and the degree of mantle melting, magma supply, and eruption rate are greatest (Clague, 1987). During the shield stage, tholeiitic magma is typically stored in a shallow (~3–7 km depth) reservoir beneath the summit and rifts (Clague, 1987; Klein et al., 1987). Transitional and alkalic magmas, such as hawaiite and mugearite, begin erupting as a volcano moves away from the hotspot and enters a postshield stage characterized by decreased mantle melting and magma supply, freezing of shallow reservoirs, and fractionation of magma in deep (~20 km depth) reservoirs (Clague, 1987; Frey et al., 1990; Wolfe et al., 1997). Trachytes are typically erupted at the end of the postshield stage (Clague, 1987; Sinton, 1987). In the paradigm of Hawaiian volcano evolution, stages and the timing of their transitions are delimited by the composition of erupted lavas. However, we present new results from ^{238}U-^{230}Th and U-Pb dating of zircons from leucocratic plutonic xenoliths indicating that lava stratigraphy is an incomplete monitor of magmatic evolution within subsurface reservoirs. Our results indicate that diorites from Mauna Kea record postshield evolution over tens of thousands of years when the depth of magma storage increased and highly evolved lavas began erupting. In contrast, diorites and syenogabbros from Hualalai record generation of evolved alkalic magma during the shield stage, and growth of a deep composite pluton over an ~210,000 yr interval.

MAGMATISM AT MAUNA KEA AND HUALALAI VOLCANOES

Mauna Kea and Hualalai are both in their postshield stages and have erupted highly evolved magmas. At Mauna Kea, a gradual transition from shield to postshield volcanism started at ca. 370 ka, and the first eruptions of alkalic basalt occurred at ca. 250 ka (Huang and Frey, 2003). Postshield alkalic lavas and cinder cones cap both rift and off-rift areas of Mauna Kea (Wolfe et al., 1997), with some vents as young as ca. 4.5 ka (Porter, 1979). The youngest postshield lavas are the most evolved and least abundant (Wolfe et al., 1997).

While Mauna Kea follows the archetypal progression of Hawaiian volcanism, Hualalai departs from the paradigm in several respects. Based on the exposed tholeiite and alkalic lava stratigraphy, the timing of Hualalai's shield to postshield transition has been inferred to be between ca. 130 ka and 100 ka (Moore and Clague, 1991; Cousens et al., 2003). Postshield alkalic basalts have erupted at Hualalai since at least 25 ka, with the most recent erupted at A.D. 1800–1801 (Moore et al., 1987; Moore and Clague, 1991). Hualalai is distinctive because trachytes erupted at ca. 100 ka from its three rift zones during the apparent beginning of the postshield stage rather than near the end (Clague and Bohrson, 1991; Cousens et al., 2003), as at other Hawaiian volcanoes. These trachytes have Pb isotope compositions that differ from the shield-stage tholeiites and oceanic crust that presumably compose most of the subvolcanic basement, which rules out an origin by anatexis (Cousens et al., 2003). Instead, their compositions suggest derivation by >90% fractional crystallization of alkalic or transitional basalt (Cousens et al., 2003; Shamberger and Hammer, 2006). The alkalic affinity and unusual timing of evolved magmagenesis at Hualalai suggest atypical processes at depth.

INSIGHT FROM XENOLITHS

A unique perspective of magmatic evolution and extreme differentiation at Mauna Kea and Hualalai is provided by leucocratic plutonic xenoliths hosted in postshield lavas and tephra cones. At Mauna Kea, leucocratic xenoliths are diorite and rare quartz tonalite (Fodor, 2001). The diorites are frozen hawaiite and mugearite magmas formed by >60% fractional crystallization of alkalic basalt, whereas the quartz tonalite fractionated from tholeiitic magma (Fodor, 2001). Leucocratic xenoliths from Hualalai are alkalic and include syenogabbros, diorites, monzodiorites, and anorthosites, which represent liquid or cumulate compositions (Shamberger and Hammer, 2006) previously identified as "syenites" (e.g., Moore et al., 1987; Clague, 1987; Cousens et al., 2003). Bulk compositions, phase equilibria, and mineral chemistry indicate that Hualalai's leucocratic xenoliths are frozen magmas that crystallized at pressures of ~300–700 MPa near the bottom of the oceanic crust and are the products of ≥65% fractional crystallization of a transitional or alkalic basalt parent (Shamberger and Hammer, 2006). Based on petrologic evidence indicating that the ca. 100 ka trachytes fractionated from magmas such as those represented by the leucocratic xenoliths, Shamberger and Hammer (2006) concluded that either Hualalai's active magma reservoir deepened and fractionated over only an ~20,000 yr interval at the shield to postshield transition, or a shallow shield reservoir existed simultaneously above a deep, spasmodically active and fractionating reservoir during a gradual transition. The new zircon ages reported here challenge the "rapid-transition" model and place quantitative constraints on the viability of the "two-chamber" model.

METHODS AND SAMPLES

Using the high-resolution CAMECA ims 1270 ion microprobe at UCLA for analysis of U-Th-Pb isotope composition, we dated single euhedral to anhedral zircons (Fig. DR1 in the GSA Data Repository[1]) from two leucocratic xenoliths erupted as blocks from a Pleistocene cinder cone located on the northwestern portion of Mauna Kea's summit (described by Fodor, 2001), and ten leucocratic xenoliths from several Holocene basalt lavas and tephra cones located along the summit of Hualalai. Analyses followed the protocols and conditions described by Reid et al. (1997) and Schmitt (2006). To assess the nature of the melts from which the zircons grew, we analyzed zircon-hosted glass and mineral inclusions (Fig. DR1) from two xenoliths by electron microprobe, as well as rare earth element (REE) concentrations in zircons from two Hualalai xenoliths by ion microprobe.

[1]GSA Data Repository item 2007179, Table DR1 (U-Th results), Table DR2 (U-Pb results), Table DR3 (melt inclusion compositions), Table DR4 (REE results), Figure DR1 (images of zircons), and Figure DR2 (REE plot), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

RESULTS

Mauna Kea zircons (n = 10) yield an apparent ^{238}U-^{230}Th isochron age of 76^{+84}_{-48} ka (2σ), with a mean square of weighted deviates (MSWD) of 3.7 that is outside the 95% confidence interval expected for a single age population (cf. Mahon, 1996), and show an apparent range of ages within each xenolith (Fig. 1). Based on the mixture model of Sambridge and Compston (1994), and assuming an initial Th-isotope activity ratio such as that of young Hawaiian lavas (1.03 ± 0.06; Sims et al., 1999), the Mauna Kea zircons can represent a bimodal population with ages of 122^{+88}_{-48} ka and 64^{+24}_{-20} ka (2σ) in proportions of 35% and 65%, respectively (Fig. 1).

Hualalai zircons form two groups defined by their ^{238}U-^{230}Th composition (Table DR1) and apparent isochron ages (Fig. 1). One group (n = 25) yields a weighted isochron age of 41 ± 9 ka (2σ) with an MSWD of 1.5, and another group (n = 24) yields a weighted isochron age of 257^{+60}_{-46} ka (2σ; MSWD = 0.69). U-Pb analyses of zircons (n = 24; Table DR2) from the older group yield a common Pb and ^{230}Th disequilibrium-corrected (Schärer, 1984) ^{238}U-^{206}Pb age of 261 ± 28 ka (2σ; MSWD = 1.8), which is concordant with their ^{238}U-^{230}Th isochron age (Fig. 1). Zircons from single Hualalai xenoliths fall in one age group or the other, except for two zircons from two ca. 40 ka group xenoliths (Fig. 1). These two zircons yield model ages of ca. 250 ka and ca. 100 ka (Fig. 1). Zircon U and Th concentrations range between 100 ppm and 500 ppm, but several crystals contain >1000 ppm of each element (Table DR1). Inclusions within Hualalai zircons from the ca. 250 ka group are crystal-free trachyte to rhyolite glass (Table DR3), as well as plagioclase, alkali feldspar, and clinopyroxene. REE concentrations in Hualalai zircons (Table DR4) are typical of zircon from evolved alkalic magmas (Fig. DR2).

DISCUSSION

Crystallization of Zircon in Mauna Kea and Hualalai Magmas

The high REE concentrations and significant Eu anomalies (Table DR4; Fig. DR2) suggest that zircon saturation in diorite magma at Hualalai was achieved partly by fractionation of plagioclase. The large variability (up to several orders of magnitude) in REE, U, and Th concentrations of the zircons (Tables DR1–DR4), as well as a range of euhedral to anhedral crystal shapes, suggests an assortment of growth conditions in melt-rich to melt-poor magma. The trachyte inclusions in Hualalai zircons are frozen melts captured late in the crystallization sequence of their parent diorite magma, as evidenced by the anhedral shape of their host zircons (Fig. DR1). Nevertheless, early growth and accumulation produced cumulus zircons in some xenoliths (Clague and Bohrson, 1991). The leucocratic xenoliths, ca. 100 ka trachytes, and melt inclusions fall within the general fractionation trend for suites of mafic-to-felsic alkalic magmas (Shamberger and Hammer, 2006).

Timing of Alkalic Magma Generation and Its Relation to Volcanism

The zircon ages provide insight into the timing of alkalic magma generation and establish a link between Hawaiian volcanoes with dif-

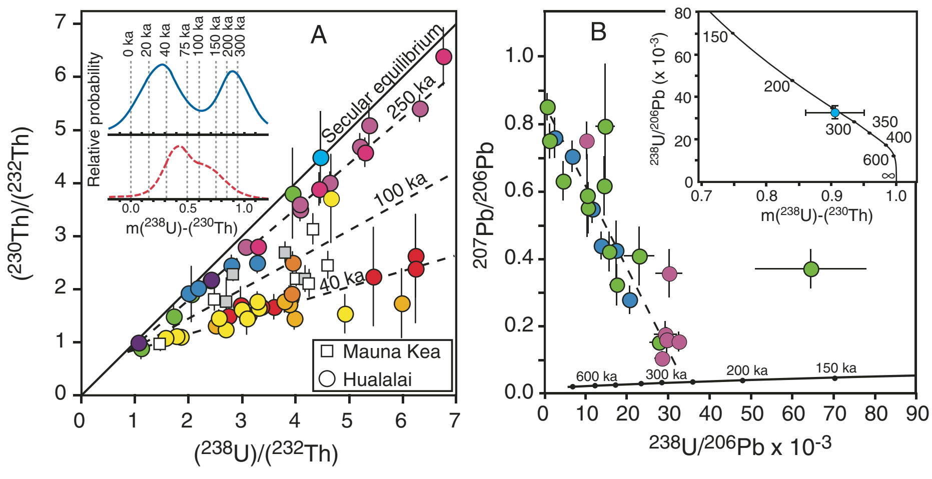

Figure 1. A: ^{238}U-^{230}Th isochron diagram showing composition of Hualalai (circles) and Mauna Kea (squares) zircons and reference isochrons (dashed lines). Zircons from single xenoliths are the same color, and each datum represents one analysis of a single zircon, except for two core and rim pairs (Table DR1). Bimodal age populations are apparent from probability density function curves (inset) of model ^{238}U-^{230}Th isochron slopes (m) for individual Hualalai (blue solid) and Mauna Kea (red dashed) zircons. B: Concordia diagram showing uncorrected ^{238}U-^{206}Pb-^{207}Pb compositions of Hualalai zircons from the older group in A, and concordia intercept at ca. 250 ka. Concordia curve is modified to account for an initial ^{230}Th deficit (Wendt and Carl, 1985), assuming $U/Th_{zircon/melt}$ = 3.6 (Condomines, 1997). Inset shows concordancy of U-Th and U-Pb ages calculated from ^{238}U-^{230}Th isochron slope and corrected ^{238}U-^{206}Pb.

ferent extrusive records. The Mauna Kea xenoliths record magmatic evolution as postshield volcanism changed to highly evolved compositions and the level of magma storage deepened. Between ca. 100 ka and 65 ka, the composition of Mauna Kea's postshield lavas changed from alkalic basalt (Hamakua volcanics) to hawaiite and mugearite (Laupahoehoe volcanics) as Mauna Kea moved away from the hotspot center and magma supply decreased (Wolfe et al., 1997). This decreased supply caused shallow and intermediate-depth chambers and conduits to freeze, and led to ponding and fractionation of basalts in a deep (~20 km depth) reservoir (Frey et al., 1990; Wolfe et al., 1997). The zircon ages delimit the generation of Mauna Kea diorite to the interval between Hamakua and Laupahoehoe volcanism (Fig. 2). Further geochronology may reveal additional age populations. Taken together with a compositional affinity to Laupahoehoe lavas (Fodor, 2001), the ages suggest that the diorites are plutonic samples of the earliest Laupahoehoe magmas. The apparent span of zircon ages in single xenoliths might reflect protracted crystallization of a single batch of evolved magma over tens of thousands of years. However, the high MSWD and apparent bimodal age population (Fig. 1) suggest that diorite magma recycled antecrystic zircons from older, yet related intrusions, as is recognized in arc and mid-oceanic-ridge magmas (e.g., Bacon and Lowenstern, 2005; Schwartz et al., 2005). Hence, the ages of Mauna Kea diorites conform to the canonical view of Hawaiian volcano evolution and generation of highly fractionated magmas. They suggest a dynamic plutonic environment where newly fractionated magmas intrude compositionally similar intrusions and recycle their crystals.

At Hualalai, the zircon ages reveal two previously unrecognized episodes of extreme differentiation. Hualalai's leucocratic xenoliths have been presumed to be cogenetic and essentially coeval with the ca. 100 ka trachytes (e.g., Moore et al., 1987; Cousens et al., 2003; Shamberger and Hammer, 2006). Instead, the new xenolith ages record episodes of extreme differentiation ~150,000 yr before and 60,000 yr after the trachytic volcanism. This bimodal age distribution suggests that Hualalai underwent just two episodes of extreme fractionation, in addition to that associated with the ca. 100 ka trachytes, or that only two of several frozen reservoirs have been intersected and sampled by summit-bound eruptions of alkalic basalt. The coherent zircon age populations, as well as similar core and rim ages for single crystals (Table DR1; Fig. 1), suggest that each batch of diorite magma evolved for $\leq 10^4$ years. This duration of evolution appears to be characteristic of highly evolved magmas within other large oceanic volcanoes (e.g., Johansen et al., 2005). The two old zircons from ca. 40 ka diorite (Fig. 1) may be xenocrysts scavenged from precursor intrusions, including material related to the ca. 100 ka trachytes. Conceivably, the two episodes of fractionation could have led to eruptions of trachytic or similar evolved lavas. However, Hualalai's shallow shield and postshield stratigraphy, as sampled by nine water well cores and blocks from maar-forming eruptions at seven localities in three quadrants of the edifice flanks, does not contain trachytes older or younger than ca. 100 ka (Cousens et al., 2003). The lack of 250 ka or 40 ka trachyte lavas suggests that the extreme fractionation evidenced by the xenoliths did not lead to volcanic eruption. Moreover, it demonstrates that chamber overpressure and ensuing volcanic activity do not necessarily accompany magma differentiation by extreme crystal fractionation.

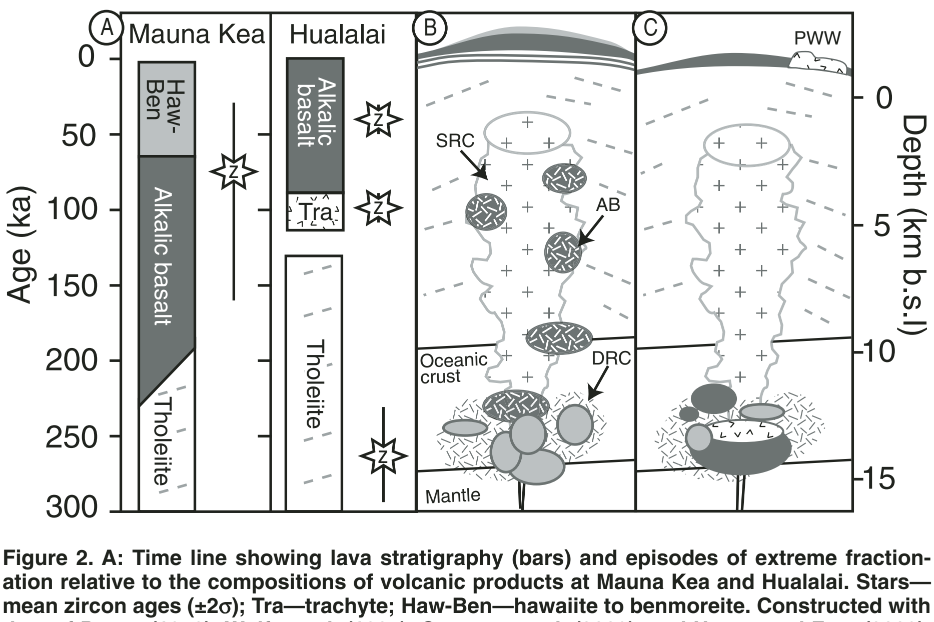

Figure 2. A: Time line showing lava stratigraphy (bars) and episodes of extreme fractionation relative to the compositions of volcanic products at Mauna Kea and Hualalai. Stars—mean zircon ages ($\pm 2\sigma$); Tra—trachyte; Haw-Ben—hawaiite to benmoreite. Constructed with data of Porter (1979), Wolfe et al. (1997), Cousens et al. (2003), and Huang and Frey (2003). B–C: Schematic cross sections of present-day Mauna Kea (B) and Hualalai (C), showing intrusive complex and levels of magma storage inferred from lava and xenolith compositions. SRC—shallow reservoir cumulates and intrusions; DRC—deep reservoir cumulates and intrusions; AB—frozen postshield (Hamakua) alkalic basalt and cumulates; PWW—Puu Waawaa trachyte.

Protracted Stage Transition and Multiple Magma Chambers at Hualalai

The ca. 250 ka xenoliths from Hualalai record the generation of evolved alkalic magma at least 120,000 yr prior to the tholeiitic shield to postshield alkalic stage transition inferred from lava stratigraphy. This early generation of alkalic magma suggests extended transition between shield and postshield stages and simultaneous evolution of chemically distinct magma reservoirs at different depths. A protracted shield to postshield transition has not been previously recognized at Hualalai but is apparent in the eruptive stratigraphies of other Hawaiian volcanoes. At Mauna Kea and East Maui volcanoes, the volcanic stratigraphy at the shield to postshield transition is composed of alternating lavas of tholeiitic and alkalic basalt, which erupted over durations on the order of 10^5 years and are thought to reflect a somewhat gradual change to smaller amounts of mantle melting and magma supply (Chen et al., 1991; Frey et al., 1991). The xenolith ages reveal that despite different extrusive records, both Hualalai and Mauna Kea generated alkalic and evolved magma at the shield to postshield transition over an extended time interval.

Generation of alkalic magma at ca. 250 ka during Hualalai's tholeiitic shield stage (Fig. 2) may mark a short-lived episode of decreased mantle melting and diminished magma supply that led to extreme fractionation. Alternatively, coeval tholeiitic and alkalic magmatism could reflect shield-stage magma chambers at different depths. During the shield stage, the shallow and any deep reservoirs are kept hot by a high throughput of tholeiitic magma so that cooling and fractionation are minimal and significant volumes of evolved magmas are not generated (Clague, 1987). Even if cooling-driven crystallization occurs, evolved alkalic magmas will not be generated in the shallow reservoir because low-pressure fractionation of tholeiitic basalt does not yield residual alkalic melts (Sack et al., 1987). Alkalic or transitional basalt can be generated from tholeiitic basalt if fractionation occurs at pressures $\geq$300 MPa within the deep portions of the volcanic system (Naumann and Geist, 1999), and these might eventually fractionate to trachyte. The Hualalai diorites apparently crystallized at pressures >300 MPa and are likely to derive from fractionation of a transitional or mildly alkalic basalt (Shamberger and Hammer, 2006). Hence, fractionation of tholeiitic basalt to produce transitional basalt in a deep, crystallizing magma reservoir within the shield stage could yield the ca. 250 ka Hualalai diorites.

Although alkalic and tholeiitic lavas are interbedded at the transitions between the shield and pre- or postshield stages (e.g., Hammer et al., 2006; Chen et al., 1991), alkalic volcanism within the shield stage is rare. Nevertheless, young alkalic basalts that erupted from the submarine rift zone of adjacent Mauna Loa volcano indicate that alkalic magmas may be generated by fractionation of tholeiite in a deep reservoir beneath an active shallow reservoir within the shield stage (Wanless et al., 2006). In any scenario, ponding of alkalic magmas at deep levels while essentially coeval tholeiite reached shallow levels is problematic. Perhaps magmas bypass one another because the main conduit is composed of irregular dikes, sills, and chambers (e.g., Wanless et al., 2006). In contrast, the ca. 40 ka diorites that crystallized within the period of postshield volcanism suggest an origin by fractionation of mildly alkalic postshield magma, although at similar depths as the ca. 250 ka diorites. Despite contrasting fidelity to the archetypal progression of volcanism, Hawaiian volcanoes may generate short-lived and highly fractionated magmas over a protracted interval during the transition from shield to postshield stages. These magmas add to the endogenous structure of individual volcanoes, yet are not always represented in the extrusive stratigraphic record.

ACKNOWLEDGMENTS

We thank A. Schmitt, M. Grove, F. Kyte, I. Lyles, and J. Boyce for help and discussions, and are grateful to C. Bacon, J. Lowenstern, and M. Reid for reviews. This work was supported by a California State University–Northridge research award to Vazquez, and National Science Foundation grant EAR-0449888 to Hammer. The ion microprobe facility at the University of California–Los Angeles is partly funded by a grant from the Instrumentation and Facilities Program, National Science Foundation.

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Manuscript received 30 October 2006
Revised manuscript received 1 March 2007
Manuscript accepted 23 March 2007

Printed in USA